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New Results from High Energy Gamma-Ray Astronomy

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Abstract. High energy gamma-ray astronomy has recently made significant progresss through ground-based instruments like the *H.E.S.S.* array of imaging atmospheric Cherenkov telescopes. The unprecedented angular resolution and the large field of view has allowed to spatially resolve for the first time the morphology of gamma-ray sources in the TeV energy range. The experimental technique is described and the types of sources detected and still expected are discussed. Selected results include objects as different as a Galactic binary Pulsar, the Galactic Center and Supernova Remnants but they also concern the diffuse extragalactic optical/infrared radiation field. Finally, a scan of the Galactic plane in TeV gamma rays is described which has led to a significant number of new TeV sources, many of which are still unidentified in other wavelengths. The field has a close connection with X-ray astronomy which allows the study of the synchrotron emission from these very high energy sources.

Keywords. radiation mechanisms: nonthermal, pulsars, Galaxy: center, acceleration of particles, supernova remnants, gamma rays: observations, cosmology: observations.

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1. Imaging Air Cherenkov Telescopes and the H.E.S.S. experiment

The principles of the Air Cherenkov Technique were invented in the 1950ies, with a first astronomical success in the late 1980ies, when the *Whipple* telescope in Arizona detected the Crab Nebula (Weekes *et al.* (1989)).

The recent progress in VHE γ-ray astronomy with the *H.E.S.S.* experiment in Namibia was possible through several new developments in the 1990ies (i) the stereoscopic technique, pioneered by the German/Spanish/Armenian *HEGRA* experiment on La Palma (ii) the development of fine pixel "cameras" as focal plane detectors (*CAT* telescope in the French Pyrenees) (iii) the realization of the spatial extension of most of the expected γ-ray sources and thus the necessity for wide field-of-view (FoV) detectors allowing also sky surveys, and (iv) the need for the detection of "many", spatially extended nearby sources to solve the problem of Cosmic Ray origin in our Galaxy. It is therefore advantageous to observe the Galactic disk in the southern sky. This led to the choice of the Gamsberg area in Namibia in Southern Africa.

Fig.1 shows two of the four telescopes of the *High Energy Stereoscopic System (H.E.S.S.)* at 1800 m.a.s.l. It is operated by a large collaboration led by the Max Planck Institute for Nuclear Physics in Heidelberg (http://www.mpi-hd.mpg.de/hfm/HESS/HESS/html). The four telescopes operate in coincidence, at the corners of a square with 100 meters side lengths, just inside the Cherenkov light cone of an electromagnetic shower of a few ns duration. It is produced by a high-energy cosmic γ-ray hitting the atmosphere and exhibits the maximum of the secondary electron/positron density at a height of about 10 km .

Such a stereoscopic device allows - in the manner of a land surveyor - a purely geometric reconstruction of the direction of the primary photon. Also the primary en-

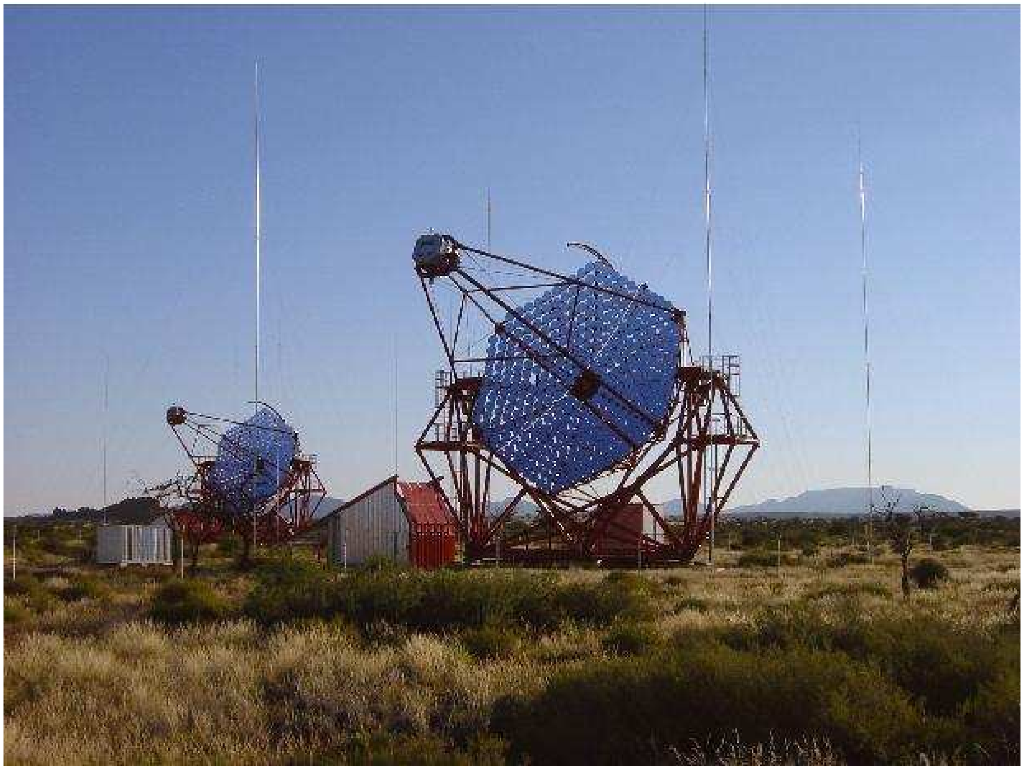

Figure 1. The *H.E.S.S.* experiment in Namibia, near the famous Gamsberg. Two of the four 13m-telescopes are shown with their "cameras" in the focal point.

ergy can be determined through a determination of the shower footpoint on the ground (Aharonian *et al.* (1997)). Gamma-ray events are distinguished from the much more frequent isotropic events due to charged Cosmic Rays through their more slender shower images in the cameras, i.e. by image analysis and the resulting cuts on the image parameters. This permits γ-ray astronomy at TeV energies (1 TeV $= 10^{12}$ eV)

The characteristics of the *H.E.S.S.* telescope system are as follows: 4 telescopes with 107 m^2 mirror surface, 4 "smart" cameras, each with 960 photomultiplyer tubes with (0.16°) FoV, leading to a total FoV of $\approx 5°$ per camera. The corresponding angular resolution of the system is better than 0.1 % per event, the energy resolution is about 10 to 15% per event, and the energy threshold (at Zenith) is about 100 GeV. The system is fully operational since December 2003.

The resulting *H.E.S.S.* sensitivity (4 telescopes) is as follows: 1 hour of observation time for a detection of an energy flux density of 10^{-11} (10^{-12}) erg cm^{-2} s^{-1} at 100 GeV (1 TeV). With this performance the Crab Nebula can be detected at Zenith in ~ 30 s. For comparison, the 1989 detection required ~ 50 hr.

2. Science with high energy gamma-ray astronomy

The two main fields of very high energy (VHE) γ-ray astronomy are High Energy Astrophysics and Observational Cosmology.

2.1. *High Energy Astrophysics*

High Energy Astrophysics concerns the most energetic and violent processes in the Universe, and in particular their nonthermal aspects. We have to expect that the nonthermal energy content U_{nonth} of relativistic baryonic particles is in most regions of the Universe comparable to the energy densities in the thermal gas U_{th} and the magnetic fields U_{mag}, i.e. $U_{nonth} \sim U_{th} \sim U_{mag}$. This should at least be true "everywhere" in galaxies and clusters of galaxies. But it holds probably also beyond, wherever cosmic structure formation with its violent, supersonic flows of baryonic matter has taken place or is still occurring. As a result of interactions of individual particles with collective excitations of the system, the particle sources and the associated nonthermal radiation should be characterized by power-law energy spectra rather than by thermal Maxwellian distributions

Because of its expected ubiquity I call this component the "Nonthermal Universe". Its study is intimately connected with that of stellar explosions, rapid outflows from galaxies, energy losses of extreme compact objects, and high-energy accretion processes up to the very largest spatial scales.

The types of VHE γ-ray sources found/*expected* in the Galaxy are Pulsar Nebulae, Supernova Remnants, X-ray Binaries ("Micro-Quasars"), Diffuse Galactic emission, *Molecular Clouds*, or possibly *new source types.* Extragalactic sources are Active Galactic Nuclei (e.g. Blazars), Radio Galaxies, *Gamma-ray Pair Halos, Starburst Galaxies, Galaxy Mergers, Clusters of Galaxies, and Gamma-Ray Bursts.*

2.2. *Observational Cosmology*

A major aspect of cosmology is cosmic structure formation. One of its consequences is the Extragalactic Background Light (EBL), the thermal, diffuse optical/infrared extragalactic background radiation from stars and Black Holes in galaxies and its re-radiation in the infrared. The EBL informs us about the epochs of galaxy formation and the history of their evolution.

TeV γ-quanta are absorbed by pair production on these low energy photons and therefore the spectra of distant extragalactic VHE γ-ray sources are expected to exhibit characteristic absorption features. They are the result of the magnitude and spectral variation of this background. Whereas a direct astronomical measurement of the EBL is very difficult, the $\gamma\gamma$-absorption is free of such complications. Its measurement for objects at different redshifts z should in principle allow even the resolution of the EBL in z. Very recently measurements of two different Blazars with known redshift that were newly discovered by the *H.E.S.S.* Collaboration have indeed been used (Aharonian *et al.* (2005a); see also the talk by J. Quinn in these Proceedings) to give the most stringent upper limit on the EBL in the optical/near-infrared band to date. It appears significantly lower than expected from the current "direct" estimates and very close to the absolute lower limit represented by the integrated light of resolved galaxies (Madau & Pozetti (2000)). Apart from resolving the EBL largely into individual galaxies, this upper limit is especially in conflict with the claims of a high EBL flux at near-infrared wavelengths (Matsumoto *et al.* (2005); Cambresy *et al.* (2001)) which was often envisaged to be the result of radiation massively produced in the early Universe ($z \sim 10$) by the first stars (Pop III). Given the strong likelyhood that Pop III stars rapidly enrich their environment with heavy elements and dust grains, such an assumption was in any case highly problematic.

Another major cosmological aspect of VHE γ-ray astronomy is an indirect Dark Matter search through the detection of annihilation radiation from the lowest-mass supersymmetric particles, called Neutralinos. Such weakly interacting massive particles are widely believed to constitute the non-baryonic Dark Matter in the Universe. From gravitational

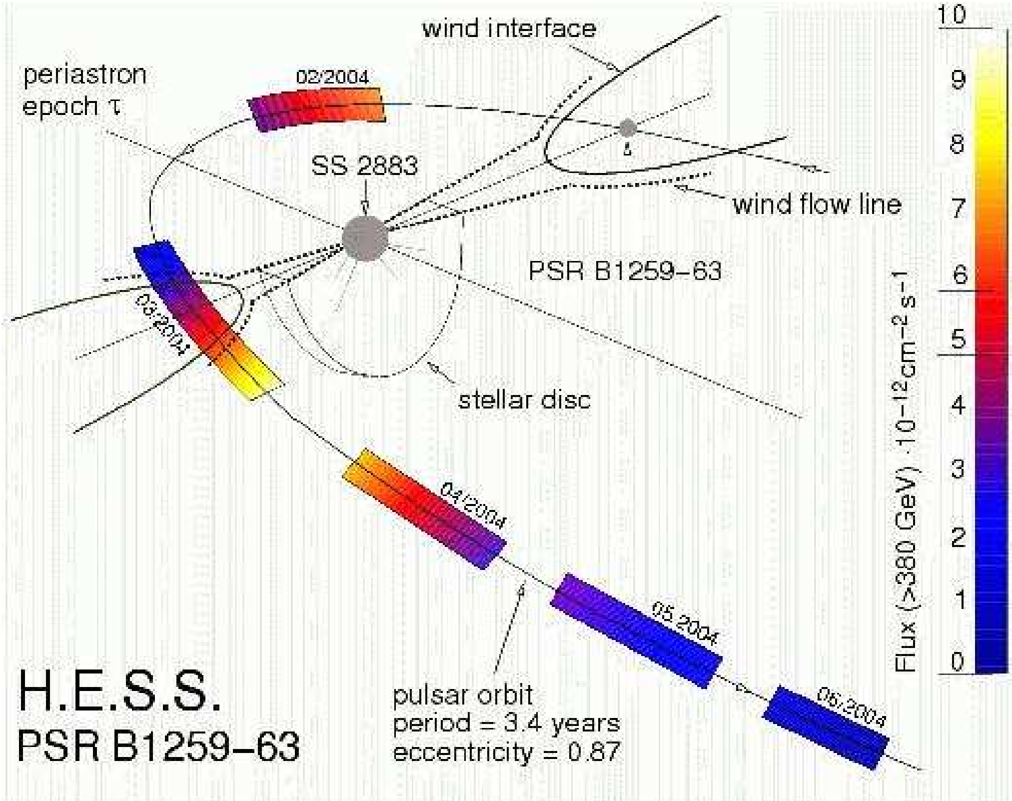

Figure 2. Orbital scheme of PSR B1259-63 with respect to the line of sight (adapted from (Johnston *et al.* (1999)). The Pulsar approaches the stellar wind equatorial plane prior to periastron "behind" it.

simulations (e.g. Navarro *et al.* (1996)) they should be concentrated with a significant density increase in the central regions of Dark Matter halos, like the Galactic center (see below).

3. Selected results

3.1. *H.E.S.S. discovery of Pulsar B1259-630*

This 48 ms Pulsar is in a 3.4 yr-period highly excentric orbit around a Be star with blackbody temperature $T_* = 23.000$ K. The particles from the Pulsar Wind are expected to be ulrarelativistic electrons and positrons, emitting Inverse Compton (IC) radiation in the stellar radiation field. Indeed the TeV-spectrum has been successfully predicted in the synchrotron/IC context (Kirk *et al.* (1999)). *H.E.S.S.* has observed the source for $\sim$ 50 hrs in 2004 around perihelion; the flux was time-variable on the scales of days (Aharonian *et al.* (2005b)).

The Be star emits a strong disk-shaped wind that confines the Pulsar Wind Nebula into a "cometary" shape (where the analogy is meant morphologically rather than physically). The periastron lies behind the star (Fig.3). Unfortunately, moonlight did not allow observations during periastron itself. The data appear nevertheless to indicate a minimum of the VHE light curve near periastron (Fig.3).

The IC losses, as measured by *H.E.S.S.*, are about a factor of 10 weaker than the

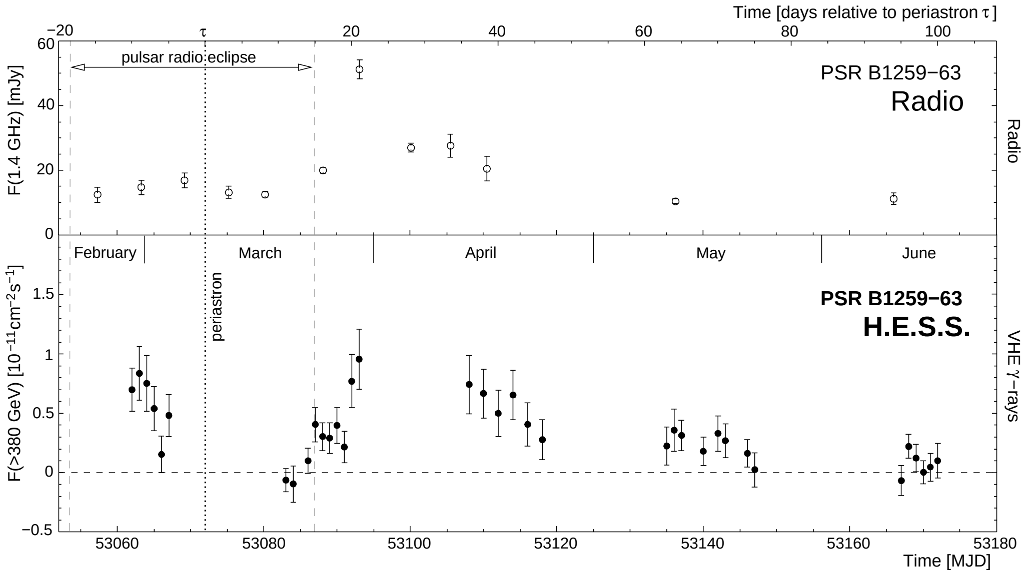

Figure 3. VHE γ-ray and unpulsed radio (Johnston *et al.* (2005)) light curves from PSR B1259-63 around its periastron passage (*dotted vertical line*).

corresponding synchrotron losses, as inferred by *INTEGRAL* (Shaw *et al.* (2004)). This determines an effective magnetic field strength $B_{\text{eff}} \approx 1$ G. In the expected Klein-Nishina regime the observed IC photon spectrum corresponds to a very hard differential electron spectrum with a power-law index $\alpha \geqslant 1.7 \pm 0.2$. It therefore cannot in turn come from a radiatively cooled electron population, and adiabatic losses must be dominant. This points to a rapidly and directionally expanding Pulsar Wind Nebula flow, resulting in a very interesting physical picture: The shocked Pulsar Wind is accelerated into a "cometary tail" flow, induced by the stellar wind. This flow is more strongly expanding outside the wind "disk" near periastron, where it is directed away from us. As a consequence its emission is in addition diminished by Doppler dis-favoritism. Both effects together lead to a local minimum of the IC flux around periastron, despite the fact that the stellar radiation field peaks at this point.

3.2. *Galactic Center region*

The innermost region of our Galaxy has an abundance of nonthermal sources, many of them Supernova Remnants. *H.E.S.S.* has observed this region and has detected the neighborhood of Sgr A* with high significance (Aharonian *et al.* (2004a)). Two discrete sources were found, one around Sgr A* itself and another one about 1° away in the Galactic Disk (see Fig.4a). This latter source is the Supernova Remnant (SNR) G0.9+0.1, dominated by a Pulsar Wind Nebula (Aharonian *et al.* (2005d). Although the statistical angular resolution of the *H.E.S.S.* observation of the Sgr A* region is more than an order of magnitude better than the one achieved in the previous detections at TeV energies (Tsuchya *et al.*(2004); Kosack *et al.* (2004)) or in the GeV range (Mayer-Hasselwander *et al.* (1998)), the *H.E.S.S.* image center cannot yet be seperated from Sgr A* itself within the present pointing accuracy of the system ($\sim$ 20 arcsec in both coordinates). The γ-ray source is apparently point-like. Therefore other properties like the energy spectrum or a possible time variability become important criteria to determine whether the γ-ray emission comes from the central Black Hole and/or its immediate environment (the accretion flow or jets), or from a more extended source in the neighborhood. No time variability has been found

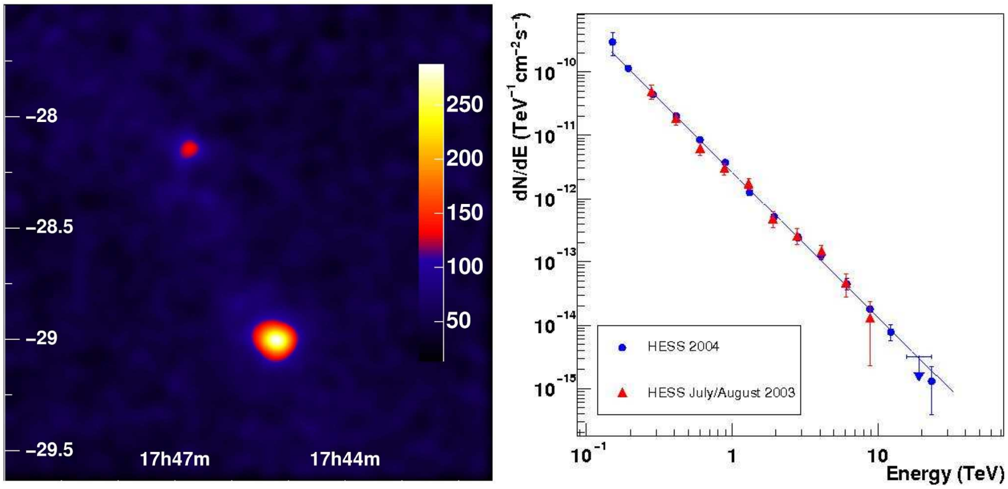

Figure 4. (Left:) *H.E.S.S.* VHE γ-ray image of the inner region of the Galaxy. The source on the lower right (*Galactic Center region*) is coincident within $1'$ of Sgr A*. The source on the upper left is the Supernova Remnant G0.9+0.1 in the Galactic plane. (Right:) VHE γ-ray spectrum of the *Galactic Center region* as obtained by the *H.E.S.S.* array. The energy spectrum is a power law and extends beyond 20 TeV.

until now. The form of the differential γ-ray spectrum $\propto E^{-2.3}$ (Fig. 4b) corresponds to a relatively hard power-law, and is therefore also consistent with freshly produced Cosmic Rays interacting with dense gas (with a hydrogen density $N_H \sim 10^3 \mathrm{cm}^{-3}$), or diffusive shock acceleration of particles still confined in the adjacent SNR Sgr A East. Theoretically there is even the possibility of a continuous transition between these two last radiation mechanisms.

The most exotic scenario would be dominant steady-state Neutralino/WIMP annihilation in the expected Dark Matter Halo centered on Sgr A*. Apart from the present difficulties to model the observed TeV spectrum within supersymmetric theories, the rest energy of the Neutralino must then be larger than the maximum energy up to which the supposed annihilation spectrum extends. This corresponds to at least 20 TeV. Since the largest particle accelerator to exist in the foreseeable future, the *LHC* in CERN, only reaches center-of-momentum energies of the order of a TeV, this particle could not possibly be discovered in accelerator experiments. Thus, if the detected γ-ray flux from the Galactic center is to be ascribed to Dark Matter annihilations, then only astrophysics can tackle this question – a very interesting perspective.

3.3. *Supernova Remnants and Cosmic Ray origin*

While the theoretical aspects are essentially understood (e.g. Völk (2004) for a recent overview), there is a shortage of γ-ray detections. The *EGRET* experiment could not unequivocally establish the detection of a shell-type SNR in the GeV-range. Also the widely publicised TeV γ-ray detection of SN 1006 by the *CANGAROO* experiment could not be confirmed by *H.E.S.S.* (Aharonian *et al.* (2005e)). The reason is in all probability the very low gas density $N_H < 0.1 \mathrm{cm}^{-3}$ (Ksenofontov *et al.* (2005)) in this object that is so bright in nonthermal X-rays (Koyama *et al.* (1995)). The second reason for the low TeV flux is the amplification of the magnetic field (Bell & Lucek (2001), Berezhko *et al.* (2003a)) which depresses the IC emission – for given synchrotron emission – compared to that in a more typical μG interstellar field strength. Meanwhile also

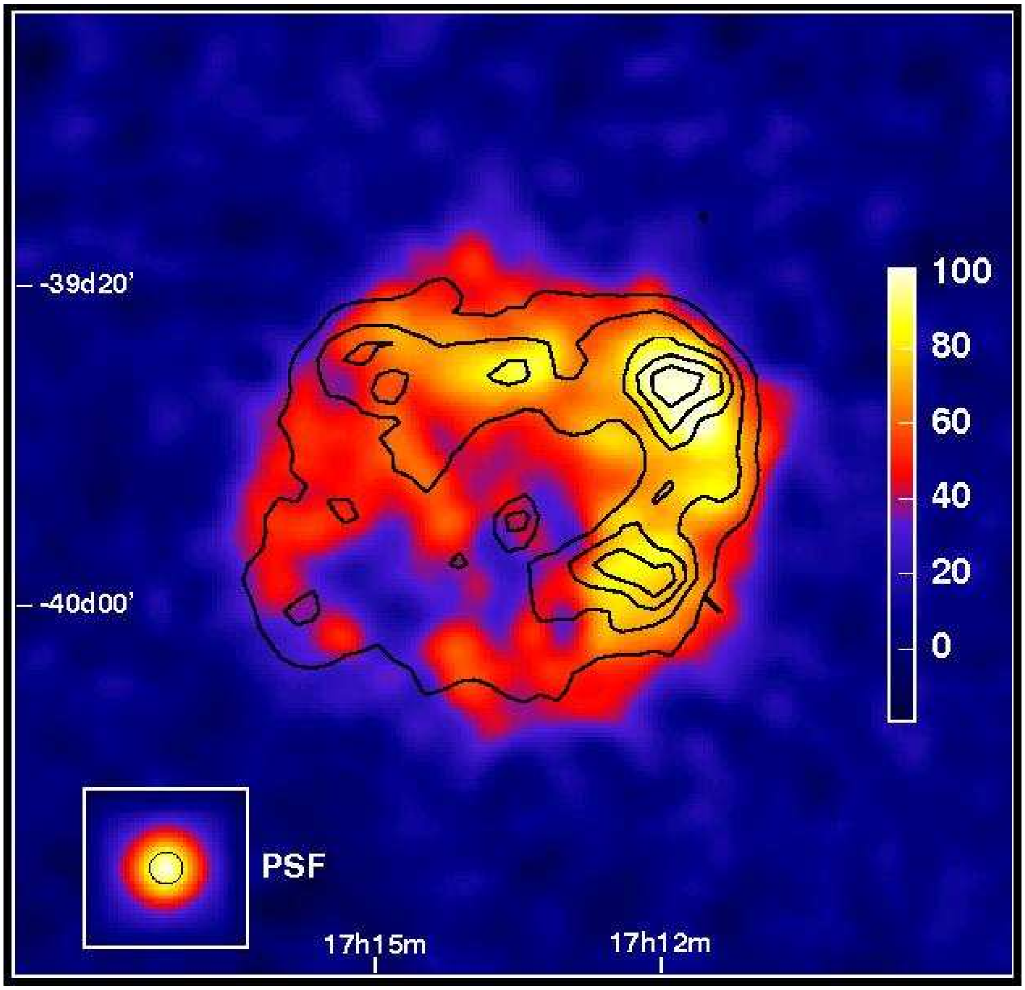

Figure 5. Spatially resolved VHE γ-ray image of the SNR RX J1713.7-3936 as obtained by the *H.E.S.S.* array. The *ASCA* hard X-ray data (*contour lines*) are shown in addition.

the *CANGAROO* collaboration has announced that it could not any more detect SN 1006 in stereoscopic re-observations (Mori (2005)).

There are only three VHE detections until now: RX J1713.7-3946 (Muraishi *et al.* (2000); Enomoto *et al.* (2002); Aharonian *et al.* (2004b)), Cas A (Aharonian *et al.* (2001)), and RX J0852.0-4622 (Katagiri *et al.* (2005); Aharonian *et al.* (2005f)).

Cas A is a thoroughly studied object in all wavelength ranges below γ-ray energies and thus amenable to a detailed application of nonlinear acceleration theory (Berezhko *et al.* (2003b)). In addition, the observations of narrow filamentary structures in nonthermal X-rays (assumed to be synchrotron radiation) by Vink & Laming (2003) can be interpreted to imply an interior magnetic field strength of 500μG (Berezhko & Völk (2004)), consistent with the theoretical analysis of the spatially integrated synchrotron spectrum. This strongly suggests Cas A as a source of nuclear Cosmic Rays, independent of all remaining uncertainties in the astronomical parameters.

The *H.E.S.S.* observations of RX J1713.7-3946 have for the first time resolved the morphology of an extended object in VHE gamma rays (Fig.5). The overall shell structure

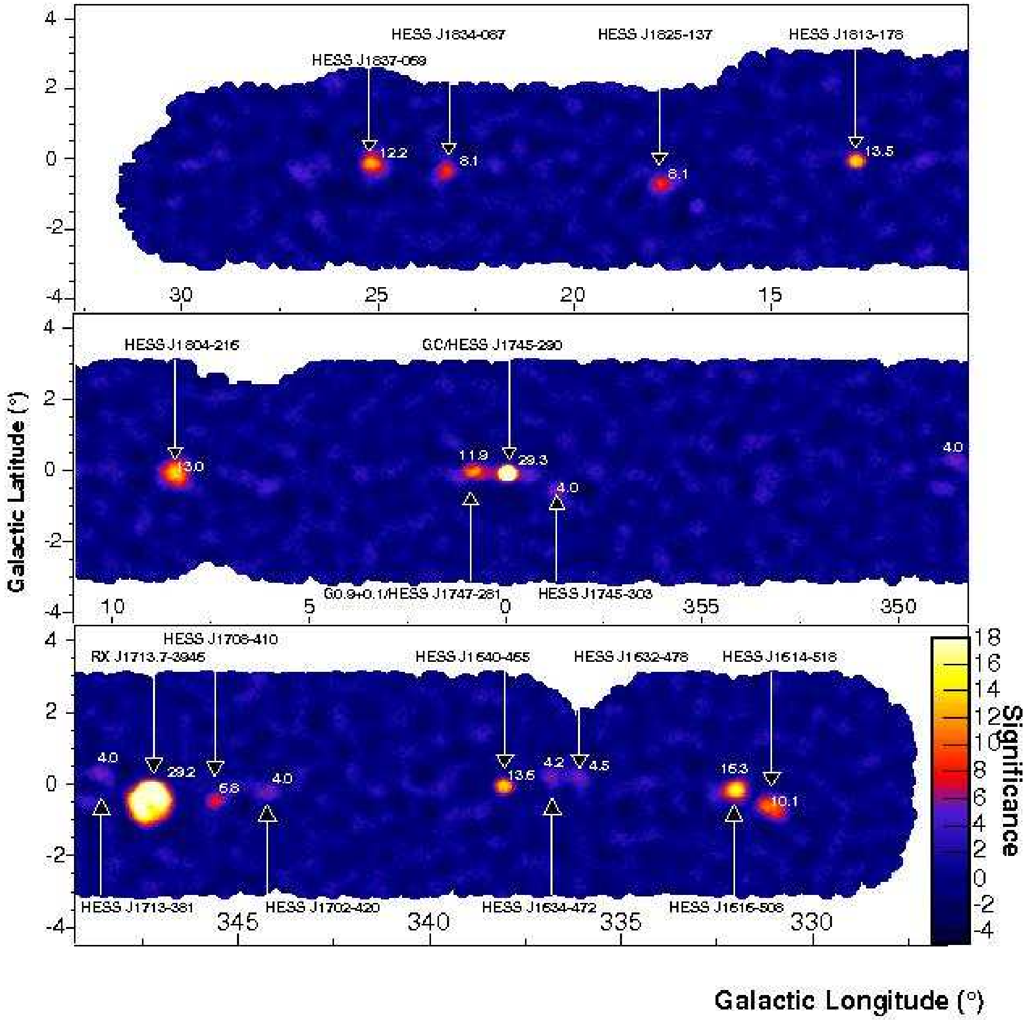

Figure 6. *H.E.S.S.* scan of the Galactic Plane between $\pm 30^\circ$ in longitude and $\pm 3^\circ$ in latitude. The sources indicated are detected at a significance level greater than 4σ.

coincides closely in hard X-rays and gamma rays. Despite the complex structure this is unambiguous proof of the acceleration of charged particles to energies beyond 100 TeV. The most recent data show in addition that below about 10 TeV the photon spectrum can be approximated by a power law in energy with an index close to 2.0. Such a spectrum is clearly consistent with diffusive shock acceleration. More detailed studies are in progress.

RX J0852.0-4622, also called "Vela Jr", was, like RX J1713.7-3946, first detected with the *ROSAT* telesope in X-rays (Aschenbach (1998)). The object has a radius of $\sim 1^\circ$, twice that of RX J1713.7-3946 and thus four times the radius of the full Moon. The TeV γ-ray morphology correlates again very well with the X-ray image, and the energy spectrum – not yet very precisely determined – can be fit by a power law with photon index 2.1. In this sense Vela Jr is similar to RX J1713.7-3946. Its apparently regular spherical shape and high γ-ray flux, comparable with that of the Crab Nebula, make it an ideal object for further studies.

4. The *H.E.S.S.* survey of the Galactic plane

In 2004 *H.E.S.S.* has completed the first 230 hour part of a VHE survey of the Galactic plane, covering $-30^\circ < \ell < 30^\circ$ in longitude and $-3^\circ < b < 3^\circ$ in latitude (Aharonian *et al.* (2005g)). The average flux sensitivity of the survey corresponds to ~ 3 percent of the Crab Nebula (Fig. 6). Including recent re-observations of candidate sources from the initial survey fourteen previously unknown VHE sources have been found up to now (Aharonian *et al.* (2006)). Most of the sources are still un-identified in other wavelength ranges.

In this manner for the first time a TeV instrument has investigated not only source candidates that were well known from other wavelength ranges, but did a successful blind search. The search for counterparts in other wavelength ranges is ongoing. Most known counterpart candidates are young Pulsar Wind Nebulae or SNRs. The new sources have triggered a worldwide activity with satellite X-ray instruments like *INTEGRAL, ASCA, XMM* and *Astro-E2*, and ground-based radio telesopes.

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